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(54) **SECURE ACTIVATION OF A DOWNHOLE DEVICE**

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166/66, 250.01, 55.1, 381, 65.1, 72; 175/4.54,
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See application file for complete search history.

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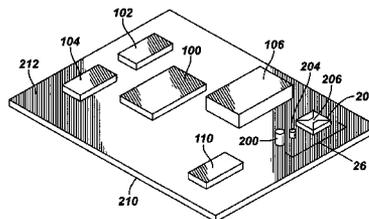
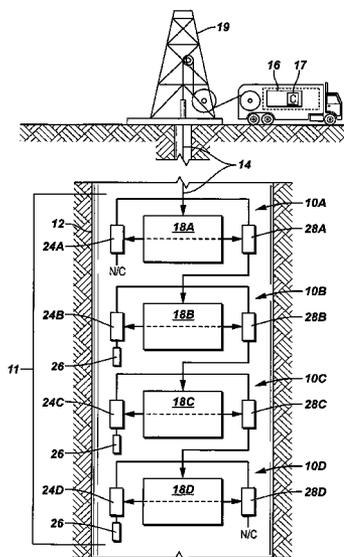
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(57) **ABSTRACT**

A system includes a well tool for deployment in a well, a controller, and a link coupled between the controller and the well tool. The well tool comprises plural control units, each of the plural control units having a microprocessor and an initiator coupled to the microprocessor. Each microprocessor is adapted to communicate bi-directionally with the controller. The controller is adapted to send a plurality of activation commands to respective microprocessors to activate the respective control units. Each activation command containing a unique identifier corresponding to a respective control unit.

17 Claims, 4 Drawing Sheets



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FIG. 1

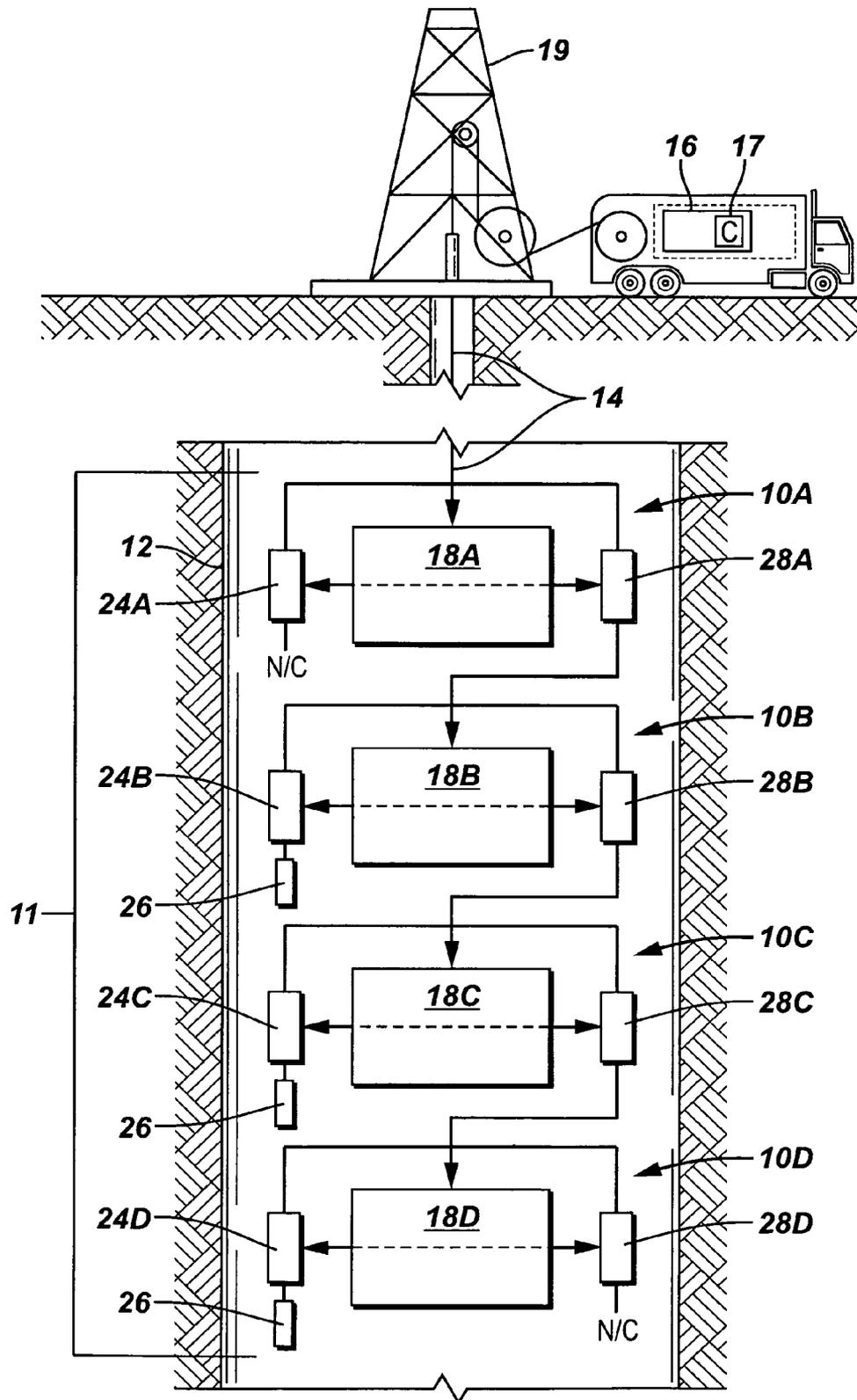


FIG. 3

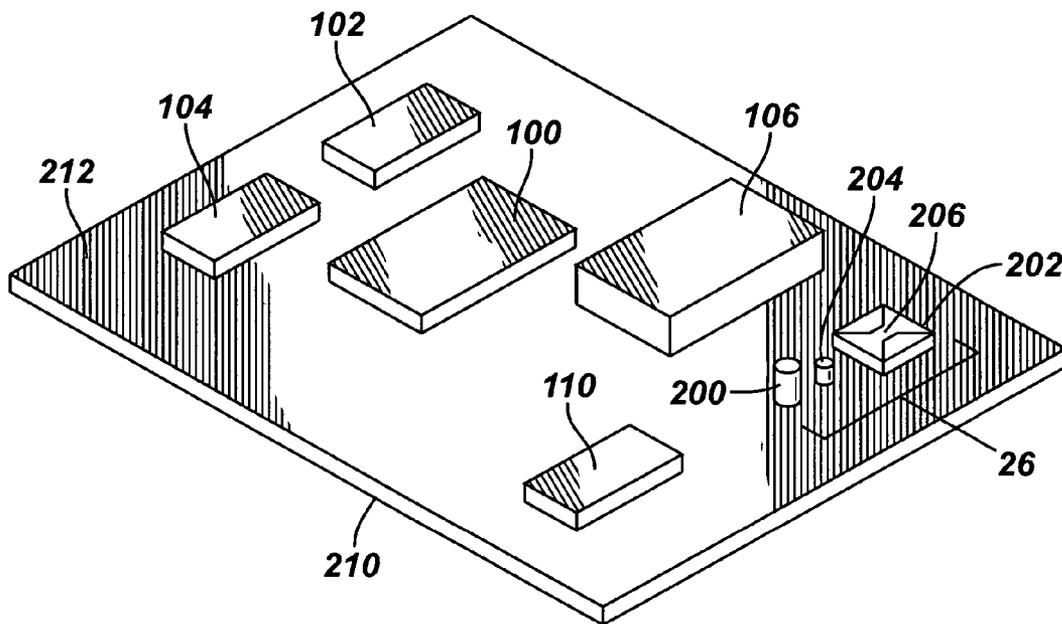
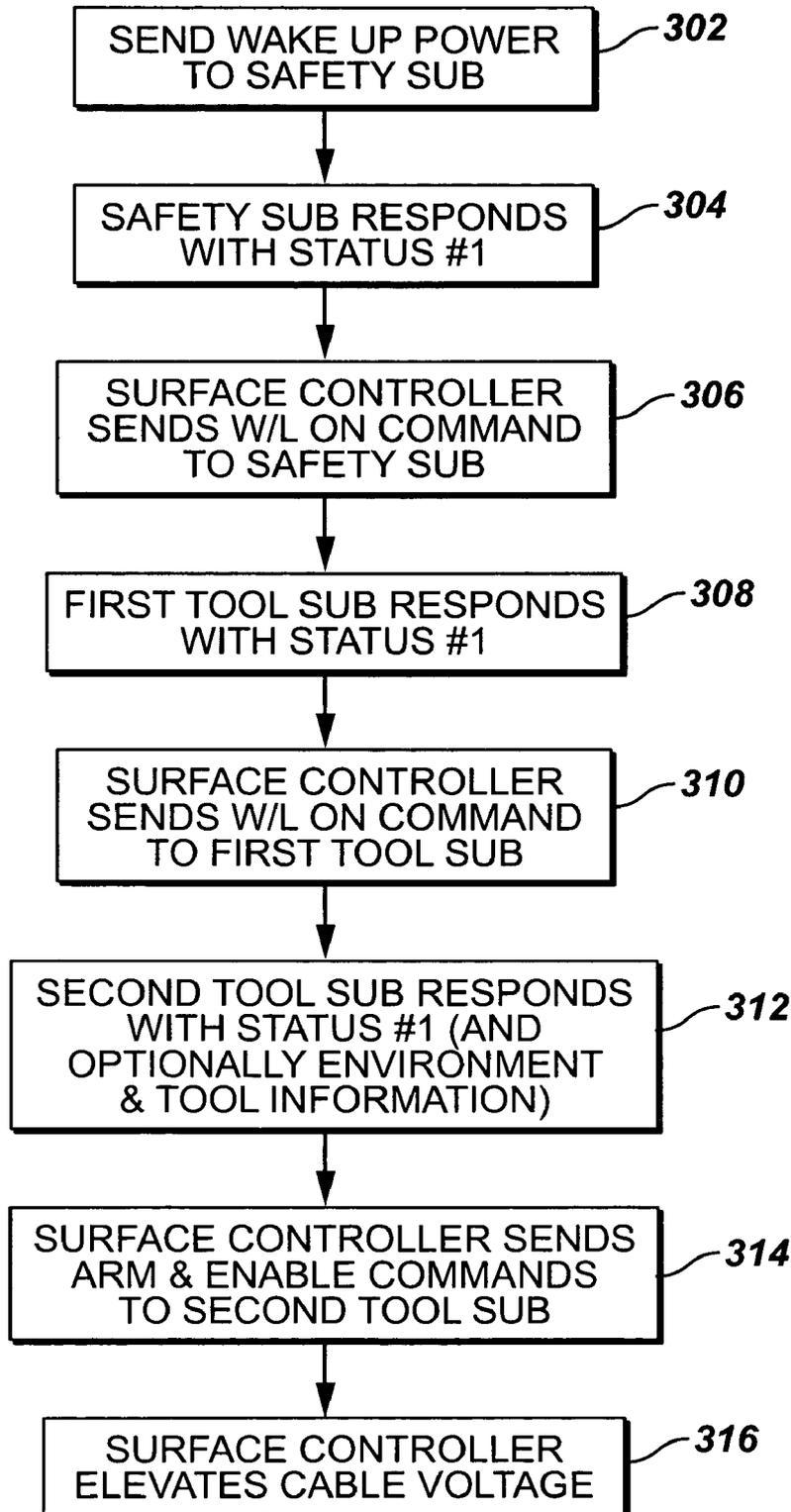


FIG. 4



1

SECURE ACTIVATION OF A DOWNHOLE DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. Ser. No. 10/076,993, filed Feb. 15, 2002, which is a continuation-in-part of U.S. Ser. No. 09/997,021, filed Nov. 28, 2001, now U.S. Pat. No. 6,938,689, which is a continuation-in-part of U.S. Ser. No. 09/179,507, filed Oct. 27, 1998, now U.S. Pat. No. 6,283,227.

This application also claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application Ser. No. 60/498,729, entitled, "Firing System for Downhole Devices," filed Aug. 28, 2003.

Each of the referenced applications is hereby incorporated by reference.

TECHNICAL FIELD

The invention relates generally to secure activation of well tools.

BACKGROUND

Many different types of operations can be performed in a wellbore. Examples of such operations include firing guns to create perforations, setting packers, opening and closing valves, collecting measurements made by sensors, and so forth. In a typical well operation, a tool is run into a wellbore to a desired depth, with the tool being activated thereafter by some mechanism, e.g., hydraulic pressure activation, electrical activation, mechanical activation, and so forth.

In some cases, activation of downhole tools creates safety concerns. This is especially true for tools that include explosive devices, such as perforating tools. To avoid accidental detonation of explosive devices in such tools, the tools are typically transferred to the well site in an unarmed condition, with the arming performed at the well site. Also, there are safety precautions taken at the well site to ensure that the explosive devices are not detonated prematurely.

Another safety concern that exists at a well site is the use of wireless devices, especially radio frequency (RF), devices, which may inadvertently activate certain types of explosive devices. As a result, wireless devices are usually not allowed at a well site, thereby limiting communications options that are available to well operators. Yet another concern associated with using explosive devices at a well site is the presence of stray voltages that may inadvertently detonate explosive devices.

A further safety concern with explosive devices is that they may fall into the wrong hands. Such explosive devices pose great danger to persons who do not know how to handle the explosive devices or who want to maliciously use the explosive devices to harm others.

SUMMARY OF THE INVENTION

In general, methods and apparatus provide more secure communications with well tools. For example, a system includes a well tool for deployment in a well, a controller, and a link coupled between the controller and the well tool. The well tool includes plural control units, each of the plural control units having a microprocessor and an initiator coupled to the microprocessor. Each microprocessor is adapted to communicate bi-directionally with the controller.

2

The controller is adapted to send a plurality of activation commands to respective microprocessors to activate the respective control units. Each activation command contains a unique identifier corresponding to a respective control unit.

Other or alternative features will become apparent from the following description, from the drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of an example arrangement of a surface unit and a downhole well tool that incorporates an embodiment of the invention.

FIG. 2 is a block diagram of a control unit used in the well tool of FIG. 1, according to one embodiment.

FIG. 3 illustrates an integrated control unit, according to an embodiment.

FIG. 4 is a flow diagram of a process of activating the well tool according to an embodiment.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, numerous details are set forth to provide an understanding of the present invention. However, it will be understood by those skilled in the art that the present invention may be practiced without these details and that numerous variations or modifications from the described embodiments may be possible.

As used here, the terms "up" and "down"; "upper" and "lower"; "upwardly" and "downwardly"; "upstream" and "downstream"; "above" and "below"; and other like terms indicating relative positions above or below a given point or element are used in this description to more clearly describe some embodiments of the invention. However, when applied to equipment and methods for use in wells that are deviated or horizontal, such terms may refer to a left to right, right to left, or other relationship as appropriate.

Referring to FIG. 1, a system according to one embodiment includes a surface unit 16 that is coupled by cable 14 (e.g., a wireline) to a tool 11. The cable 14 includes one or more electrical conductor wires. In a different embodiment, the cable 14 can include fiber optic lines, either in place of the electrical conductor wires or in addition to the electrical conductor wires. The cable 14 conveys the tool 11 into a wellbore 12.

In the example shown in FIG. 1, the tool 11 is a tool for use in a well. For example, the tool 11 can include a perforating tool or other tool containing explosive devices, such as pipe cutters and the like. In other embodiments, other types of tools can be used for performing other types of operations in a well. For example, such other types of tools include tools for setting packers, opening or closing valves, logging, taking measurements, core sampling, and so forth.

In the example shown in FIG. 1, the tool 11 includes a safety sub 10A and tool subs 10B, 10C, 10D. Although three tool subs 10B, 10C, 10D are depicted in FIG. 1, other implementations can use a different number of tool subs. The safety sub 10A includes a control unit 18A, and the tool subs 10B, 10C, 10D include control units 18B, 18C, 18D, respectively. Each of the tool subs 10B, 10C, 10D can be a perforating gun, in one example implementation. Alternatively, the tool subs 10B, 10C, 10D can be different types of devices that include explosive devices.

The control units **18A**, **18B**, **18C**, **18D** are coupled to switches **24A**, **24B**, **24C**, **24D**, respectively, and **28A**, **28B**, **28C**, **28D**, respectively. The switches **28A-28D** are cable switches that are controllable by the control units **18A-18D**, respectively, between on and off positions to enable or disable electrical current flow through portions of the cable **14**. When the switch **28** is off (also referred to as “open”), then the portion of the cable **14** below the switch **24** is isolated from the portion of the cable **14** above the switch **24**. The switches **24A-24D** are initiator switches.

Although reference is made primarily to electrical switches in the embodiments described, it is noted that optical switches can be substituted for such electrical switches in other embodiments.

In the safety sub **10A**, the initiator switch **24A** is not connected to a detonating device or initiator. However, in the tool subs **10B**, **10C**, **10D**, the initiator switches **24B**, **24C**, **24D** are connected to respective detonating devices or initiators **26**. If activated to an on (also referred to as “closed”) position, an initiator switch **24** allows electrical current to flow to a coupled detonating device or initiator **26** to activate the detonating device. The detonating devices or initiators **26** are ballistically coupled to explosive devices, such as shaped charges or other explosives, to perform perforating or another downhole operation. In the ensuing discussion, the terms “detonating device” and “initiator” are used interchangeably.

As noted above, the safety sub **10A** provides a convenient mechanism for connecting the tool **11** to the cable **14**. This is because the safety sub **10A** does not include a detonating device **26** or any other explosive, and thus does not pose a safety hazard. The switch **28A** of the safety sub **10A** is initially in the open position, so that all guns of the tool **11** are electrically isolated from the cable **14** by the safety sub **10A**. Because of this feature, electrically arming of the tool **11** does not occur until the tool **11** is positioned downhole and the switch **28A** is closed. In the electrical context, the safety sub **10A** can provide electrical isolation to prevent arming of the tool **11**.

Another feature allowed by the safety sub **10A** is that the tool subs **10B**, **10C**, **10D** (such as guns) can be pre-armed (by connecting each detonating device **26**) during transport or other handling of the tool **11**. Thus, even though the tool **11** is transported ballistically armed, the open switch **28A** of the safety sub **10A** electrically isolates the tool subs **10B**, **10C**, **10D** from any activation signal during transport or other handling.

The safety sub **10A** differs from the tool subs **10B**, **10C**, **10D** in that the safety sub **10A** does not include explosive devices that are present in the tool subs **10B**, **10C**, **10D**. The safety sub **10A** is thus effectively a “dummy assembly.” A dummy assembly is a sub that mimics other tool subs but does not include an explosive.

The safety sub **10A** serves one of several purposes, including providing a quick connection of the tool **11** to the cable **14**. Additionally, the safety sub **10A** allows arming of the tool **11** downhole instead of the surface. Because the safety sub **10A** does not include explosive devices, it provides isolation (electrical) between the cable **14** and the tool subs **10B**, **10C**, **10D** so that activation (electrical) of the tool subs **10B**, **10C**, **10D** is disabled until the safety sub **10A** has been activated to close an electrical connection.

The safety sub **10A** effectively isolates “signaling” on the cable **14** from the tool subs **10B**, **10C**, **10D** until the safety sub **10A** has been activated. “Signaling” refers to power and/or control signals (electrical) on the cable **14**.

In accordance with some embodiments of the invention, the control units **18A-18D** are able to communicate over the cable **14** with a controller **17** in the surface unit **16**. For example, the controller **17** can be a computer or other control module.

Each control unit **18A-18D** includes a microprocessor that is capable of performing bi-directional communication with the controller **17** in the surface unit **16**. The microprocessor (in combination with other isolation circuitry in each control unit **18**) enables isolation of signaling (power and/or control signals) on the cable **14** from the detonating device **26** associated with the control unit **18**. Before signaling on the cable **14** can be connected (electrically) to the detonating device **26**, the microprocessor has to first establish bi-directional communication with the controller **17** in the surface unit **16**.

The bi-directional communication can be coded communication, in which messages are encoded using a predetermined coding algorithm. Coding the messages exchanged between the surface controller **17** and the microprocessors in the control units **18** provides another layer of security to prevent inadvertent activation of explosive devices.

Also, the microprocessor **100** can be programmed to accept only signaling of a predetermined communication protocol such that signaling that does not conform to such a communication protocol would not cause the microprocessor **100** to issue a command to activate the detonating device **26**.

Moreover, according to some embodiments, the microprocessor in each control unit is assigned a unique identifier. In one embodiment, the unique identifier is pre-programmed before deployment of the tool into the wellbore **12**. Pre-programming entails writing the unique identifier into non-volatile memory accessible by the microprocessor. The non-volatile memory can either be in the microprocessor itself or external to the microprocessor. Pre-programming the microprocessors with unique identifiers provides the benefit of not having to perform programming after deployment of the tool **11** into the wellbore **12**.

In a different embodiment, the identifiers can be dynamically assigned to the microprocessors. For example, after deployment of the tool **11** into the wellbore **12**, the surface controller **12** can send assignment messages over the cable **14** to the control units such that unique identifiers are written to storage locations accessible by the microprocessors.

FIG. 2 shows a sub in greater detail. Note that the sub **10** depicted in FIG. 2 includes a detonating device **26**; therefore, the sub **10** depicted in FIG. 2 is one of the tool subs **10B**, **10C**, and **10D**. However, if the sub **10** is a safety sub, then the detonating device **26** would either be omitted or replaced with a dummy device (without an explosive).

The control unit **18** includes a microprocessor **100** (the microprocessor discussed above), a transmitter **104**, and a receiver **102**. Power to the control unit **18** is provided by a power supply **106**. The power supply **106** outputs supply voltages to the various components of the control unit **18**. The cable **14** (FIG. 1) is made up of two wires **108A**, **108B**. The wire **108A** is connected to the cable switch **28**. In a different embodiment, the power supply **106** can be omitted, with power supplied from the well surface.

When transmitting, the transmitter **104** modulates signals over the wire **108B** to carry desired messages to the well surface or to another component. The receiver **102** also receives signaling over the wire **108B**.

The microprocessor **100** can be a general purpose, programmable integrated circuit (IC) microprocessor, an application-specific integrated circuit, a programmable gate array

or other similar control device. As noted above, the microprocessor **100** is assigned and identified with a unique identifier, such as an address, a numerical identifier, and so forth. Using such identifiers allows commands to be sent to a microprocessor **100** within a specific control unit **18** selected from among the plurality of control units **18**. In this manner, selective operation of a selected one of the control units **18** is possible.

The receiver **102** receives signals from surface components, where such signals can be in the form of frequency shift keying (FSK) signals. The received signals are sent to the microprocessor **100** for processing. The receiver **100** may, in one embodiment, include a capacitor coupled to the wireline **108B** of the cable **14**. Before sending a received signal to the microprocessor **100**, the receiver **102** may translate the signal to a transistor-transistor logic (TTL) output signal or other appropriate output signal that can be detected by the microprocessor **100**.

The transmitter **100** transmits signals generated by the microprocessor **100** to surface components. Such signals may, for example, be in the form of current pulses (e.g., 10 milliamp current pulses). The receiver **102** and transmitter **104** allow bi-directional communication between the surface and the downhole components.

The initiator switch **24** depicted in FIG. **1** can be connected to a multiplier **110**, as depicted in FIG. **2**. The initiator switch **24**, in the embodiment of FIG. **2**, is implemented as a field effect transistor (FET). The gate of the FET **24** is connected to an output signal of the microprocessor **100**. When the gate of the FET **24** is high, the FET **24** pulls an input voltage V_{in} to the multiplier **110** to a low state to disable the multiplier **110**. Alternatively, when the gate of the FET **24** is low, the input voltage V_{in} is unimpeded, thereby allowing the multiplier to operate. A resistor or resistors **112** is connected between V_{in} and the electrical wire **108B** of the cable **14**. In a different embodiment, instead of using the FET, other types of switch devices can be used for the switch **24**.

The multiplier **110** is a charge pump that takes the input voltage V_{in} and steps it up to a higher voltage in general by pulsing the received voltage into a ladder multiplier. The higher voltage is used by the initiator **26**. In one embodiment, the multiplier **24** includes diodes and capacitors. The circuit uses cascading elements to increase the voltage. The voltage, for example, can be increased to four times its input value.

Initially, before activation, the input V_{in} to the multiplier **24** is grounded by the switch **24** such that no voltage transmission is possible through the multiplier **110**. To enable the multiplier **110**, the microprocessor **100** sends an activation signal to the switch **24** to change the state of the switch **24** from the on state to the off state, which allows the multiplier to process the voltage V_{in} . In other embodiments, the multiplier **110** can be omitted, with a sufficient voltage level provided from the well surface.

The initiator **26** accumulates energy from the voltage generated by the multiplier **110**. Such energy may be accumulated and stored, for example, in a capacitor, although other energy sources can be used in other embodiments. In one embodiment, such a capacitor is part of a capacitor discharge unit (CDU), which delivers stored energy rapidly to an ignition source. The ignition source may be an exploding foil initiator (EFI), an exploding bridge wire (EBW), a semiconductor bridge (SCB), or a "hot wire." The ignition source is part of the initiator **26**. However, in a different implementation, the ignition source can be part of a separate element. In the case of an EFI, the rapid electrical discharge

causes a bridge to rapidly change to a plasma and generate a high pressure gas, thereby causing a "flyer" (e.g., a plastic flyer) to accelerate and impact a secondary explosive **116** to cause detonation thereof.

The sub **10** also includes a sensor **114** (or plural sensors), which is coupled (electrically or optically) to the microprocessor **100**. The sensor(s) measure(s) such wellbore environment information or tool information as pressure, temperature, tilt of the tool sub, and so forth. The wellbore environment information or wellbore information is communicated by the microprocessor **100** over the cable **14** to the surface controller **17**. This enables the surface controller **17** or well operator to make a decision regarding whether activation of the tool sub should occur. For example, if the wellbore environment is not at the proper pressure or temperature, or the tool is not at the proper tilt or other position, then the surface controller **17** or well operator may decide not to perform activation of the tool sub.

The control unit **18** also incorporates a resistor-capacitor (R-C) circuit that provides radio frequency (RF) protection. The R-C circuit also switches out the capacitor component to allow low-power (e.g., low-signal) communication. Moreover, the low-power communication is enabled by integrating the components of the control unit **18** onto a common support structure to thereby provide a smaller package. The smaller packaging provides low-power operation, as well as safer transportation and operation.

FIG. **3** shows integration of the various components of the control unit **18**, multiplier **110**, and initiator **26**. The components are mounted on a common support structure **210**, which can be implemented as a flex cable or other type of flexible circuit. Alternatively, the common support structure **210** can be a substrate, such as a semiconductor substrate, ceramic substrate, and so forth. Alternatively, the support structure **210** can be a circuit board, such as a printed circuit board. The benefit of mounting the components on the support structure **210** is that a smaller package can be achieved than conventionally possible.

The microprocessor **100**, receiver **102**, transmitter **104**, and power supply **106** are mounted on a surface **212** of the support structure **210**. Although not depicted, electrically conductive traces are routed through the common support structure **210** to enable electrical connection between the various components. In an optical implementation, optical links can be provided on or in the support structure **210**.

The multiplier **110** is also mounted on the surface **212** of the support structure **210**. Also, the components of the initiator **26** are provided on the support structure **210**. As depicted, the initiator **26** includes a capacitor **200** (which can be charged to an elevated voltage by the multiplier **110**), a switch **204** (which can be implemented as a FET), and an EFI **202**. The capacitor **200** is connected to the output of the multiplier **110** such that the multiplier **110** can charge up the capacitor **200** to the elevated voltage. The switch **204** can be activated by the microprocessor **100** to allow the charge from the capacitor **200** to be provided to the EFI **202**. The energy routed through a reduced-width region in the EFI **202**, which causes a flyer plate to be propelled from the EFI **202**. A secondary explosive **116** (FIG. **2**) can be positioned proximal the EFI **202** to receive impact of the flyer plate to thereby cause detonation. The secondary explosive can be ballistically coupled to another explosive, such as a shaped charge, or other explosive device.

FIG. **4** shows the procedure for firing the tool sub **10C** (in the string of subs depicted in FIG. **1**). Initially, the surface controller **17** sends (at **302**) "wake up" power (e.g., -60 volts DC or VDC) to the uppermost sub (in this case the

safety sub 10A). The safety sub 10A receives the power, and responds (at 304) with a predetermined status (e.g., status #1) after some period of delay (e.g., 100 milliseconds or ms).

The surface controller 17 then sends (at 306) a W/L ON command (with a unique identifier associated with the microprocessor of the safety sub 10A) to the safety sub 10A, which causes the microprocessor 100 in the safety sub 10A to turn on cable switch 28A (FIG. 1). The “wake up” power on the cable 14 is now seen by the second tool sub 10B. The tool sub 10B receives the power and responds (at 308) with status #1 after some predetermined delay.

In response to the status #1 message from the tool sub 10B, the surface controller 17 then sends (at 310) a W/L ON command (with a unique identifier associated with the microprocessor of the tool sub 10B) to the tool sub 10B. The “wake up” power is now seen by the second tool sub 10C. The second tool sub 10C responds (at 312) with a status #1 message to the surface controller 17. In response, the surface controller 17 sends (at 314) ARM and ENABLE commands to the tool sub 10C. Note that the ARM and ENABLE commands each includes a unique identifier associated with the microprocessor of the tool sub 10C. The ARM and ENABLE commands cause arming of the control unit 18C by activating appropriate switches (such as turning off the initiator switch 24C). In other embodiments, instead of separate ARM and ENABLE commands, one command can be issued.

The surface controller 17 then increases (at 316) the DC voltage on the cable 14 to a firing level (e.g., 120-350 VDC). The increase in the DC voltage has to occur within a predetermined time period (e.g., 30 seconds), according to one embodiment.

In the procedure above, the second tool sub 10C can also optionally provide environment or tool information to the surface controller 17, in addition to the status #1 message. The surface controller 17 can then use the environment or tool information to make a decision regarding whether to send the ARM and ENABLE commands.

A similar procedure is repeated for activating other tool subs. In this embodiment, it is noted that the surface controller 17 sends separate commands to activate the multiple tool subs.

While the invention has been disclosed with respect to a limited number of embodiments, those skilled in the art, having the benefit of this disclosure, will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover such modifications and variations as fall within the true spirit and scope of the invention.

What is claimed is:

1. A system comprising:

a well tool for deployment in a well;

a controller;

a link coupled between the controller and the well tool, wherein the well tool comprises plural control units, each of the plural control units having a microprocessor and an initiator coupled to the microprocessor, each microprocessor adapted to communicate bi-directionally with the controller,

wherein the controller is adapted to send a plurality of activation commands to respective microprocessors to activate the respective control units,

each activation command containing a unique identifier corresponding to a respective control unit, and

wherein each control unit includes a circuit board, the corresponding microprocessor and initiator being mounted on one planar surface of the circuit board.

2. The system of claim 1, wherein the initiator includes at least one of an exploding foil initiator, an exploding bridge wire, a hot wire, and a semiconductor bridge.

3. The system of claim 1, wherein the well tool further comprises tool subs, each tool sub comprising a corresponding control unit and an explosive, the explosive to be detonated by the initiator.

4. The system of claim 3, wherein the well tool further comprises a safety sub coupled to the tool subs, the safety sub having identical components as at least one of the tool subs except that the safety sub does not include an explosive, the safety sub to prevent aiming of the tool subs until after activation of the safety sub.

5. The system of claim 3, wherein each of the tool subs comprises a corresponding circuit board.

6. The system of claim 1, wherein the well tool further comprises explosives to be detonated by respective initiators.

7. The system of claim 1, wherein the link comprises a cable, the cable containing a fiber optic line.

8. The system of claim 1, wherein the initiator comprises an exploding foil initiator.

9. A method for use in a wellbore, comprising:
deploying a well tool into the wellbore;

communicating, over a link, between a controller and the well tool, wherein the well tool comprises plural control units, each of the plural control units having a microprocessor and an initiator coupled to the microprocessor;

each microprocessor communicating bi-directionally with the controller,

the controller sending a plurality of activation commands to respective microprocessors to activate the respective control units, each activation command containing a unique identifier corresponding to a respective control unit;

providing a circuit board in each control unit; and

mounting the microprocessor and initiator of each control unit on a flat surface of the respective circuit board, wherein the flat surface on which the microprocessor and initiator are mounted lies in one plane.

10. The method of claim 9, wherein mounting the initiator on the circuit board comprises mounting at least one of an exploding foil initiator, an exploding bridge wire, a hot wire, and a semiconductor bridge on the support structure.

11. The method of claim 9, wherein the initiator comprises an exploding foil initiator.

12. A method for use in a wellbore, comprising:

deploying a well tool into the wellbore;

communicating, over a link, between a controller and the well tool, wherein the well tool comprises plural control units, each of the plural control units having a microprocessor and an initiator coupled to the microprocessor;

each microprocessor communicating bi-directionally with the controller,

the controller sending a plurality of activation commands to respective microprocessors to activate the respective control units, each activation command containing a unique identifier corresponding to a respective control unit;

providing a flexible circuit in each control unit; and

mounting the microprocessor and initiator of each control unit on one planar surface of corresponding flex circuit.

13. The method of claim 12, wherein the initiator comprises an exploding foil initiator.

9

14. A tool for use in a wellbore, comprising:
a plurality of control units for communicating over a link
with a remote controller, wherein each of the control
units includes a microprocessor, wherein each control
unit is adapted to communicate bi-directionally with
the remote controller;
a plurality of initiators coupled to respective micropro-
cessors; and
wherein the control units are associated with unique
identifiers, and
wherein each microprocessor is responsive to an activa-
tion command containing the corresponding unique
identifier,

10

wherein each control unit comprises a flexible circuit
having one planar surface on which a respective micro-
processor and initiator are mounted.

15. The tool of claim 14, further comprising capacitors
mounted to respective flexible circuits.

16. The tool of claim 14, wherein the flexible circuits
comprise flex cables.

17. The method of claim 14, wherein the initiator com-
prises an exploding foil initiator.

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